Probabilistic risk assessment based on physical models can inform advanced hurricane risk management strategies.

An Integrated Approach to Assess and Manage Hurricane Risk in a Changing Climate

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Hurricanes, with their strong winds, heavy rainfall, and storm surges, cause much damage and loss of life worldwide. Recent disasters, such as Hurricanes Katrina in 2005 and Sandy in 2012, Cyclone Nargis in 2008, and Typhoon Haiyan in 2013, underscore the significant vulnerability of the United States and the world to landfalling hurricanes. And the impacts of these storms may worsen in the coming decades because of rapid coastal development coupled with sea-level rise and possibly increasing hurricane activity due to climate change.

Major advances in hurricane risk management are urgently needed. Given the inherent uncertainties in hurricane activity, such management should be strongly informed by probabilistic risk assessment. Furthermore, hurricane risk assessment cannot rely solely on historical records: to account for projected future changes, it should integrate physical knowledge and models with observational data.

Introduction

A physically based probabilistic hurricane risk assessment framework should integrate analysis of storm activity, hazards, and risk. Because of the limitations of historical records and the complexity of the problem, Monte Carlo (MC) methods, based on numerous synthetic simulations, are often used.
In an MC approach, large numbers of synthetic but physically possible storms, characterized by their track, intensity, and size, are simulated (with their annual frequencies estimated) under observed or climate model–simulated climate conditions. Hazard models are then used to estimate the wind, surge, and rainfall-induced flooding associated with the simulated storms. Given the estimated hazards and coastal exposure, vulnerability models can be applied to estimate storm-induced consequences (e.g., damage and/or economic losses) and thus risk. The risk assessment can in turn inform risk management.

The following sections review the main components—hurricane activity, hazards, and risk—of a physically based hurricane risk assessment framework and its application to evaluating risk mitigation strategies.

**Hurricane Activity**

Various MC methods have been developed to simulate storms that depict hurricane activity and climatology. Most of these methods (e.g., Hall and Sobel 2013; Toro et al. 2010; Vickery et al. 2000) create simulations based on the statistics of the historical storm records.

In my laboratory we apply the statistical-deterministic model developed by Emanuel and colleagues (2006, 2008). It simulates storm environments statistically but generates synthetic storms deterministically (with physical models). The large samples of synthetic storms generated by the model are in statistical agreement with the (albeit limited) observations. Moreover, as the synthetic hurricane environments can be generated for any given climate state, the model can simulate storms not only in current and past climates but also in projected future climates.

This model has been used to simulate storms in various ocean basins under projected climates over the 21st century to investigate how storm intensity and frequency may change with the changing climate (Emanuel 2013). It has also been used to simulate storms at city scales—for New York City (NYC; Lin et al. 2010a, 2012; Reed et al. 2015); Miami (Klima et al. 2011), Apalachee Bay (Lin et al. 2014), and Tampa (Lin and Emanuel 2015) in Florida; Galveston, Texas (Lickley et al. 2014); Cairns, Australia (Lin and Emanuel 2015); and Dubai in the Persian Gulf (Lin and Emanuel 2015). As an illustration, figure 1 shows a sample of 5,000 storms we simulated for NYC. These city-scale simulations can be used to analyze local hazards and risk.

**Hurricane Hazards**

Given a storm’s characteristics, hazard models can be applied to estimate the wind, surge, and rainfall-induced flooding during the storm’s landfall. Because large numbers of simulations are required for the MC-based risk analysis, the hazard models should be (computationally) “simple” (often there is a balance between accuracy and efficiency).
Wind

Various simple parametric methods have been developed to model the wind. In such an approach, one estimates the storm wind field using a parametric wind profile (e.g., Holland 1980; Jelesnianski et al. 1992) and adds an estimated background wind (Lin and Chavas 2012) to obtain the total wind field. My lab has recently developed a new wind profile (Chavas et al. 2015), motivated by the physical understanding that the canonical wind fields of mature hurricanes, although approximately circularly symmetric, cannot be described by a single mechanism.

Emanuel (2004) developed a physical model of the outer nonconvecting region of the storm, and Emanuel and Rotunno (2011) established an analytical profile that is physically valid only for the inner convecting region. We mathematically merged these two theoretical solutions to develop a complete wind profile for the entire domain of the storm (Chavas et al. 2015). This new physical model, evaluated and calibrated with various observational datasets, will have broad applications in hurricane hazard analysis.

Storm Surges

Storm surges, driven mainly by the storm surface wind and pressure, are also sensitive to coastal bathymetry and topography. Hydrodynamic surge models, basically solving coastal shallow water equations, include the SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model (Jelesnianski et al. 1992), used by the National Hurricane Center for real-time forecasting, and the Advanced Circulation (ADCIRC) model (Westerink et al. 2008). The SLOSH model is computationally more efficient, but the ADCIRC model can better resolve the physical processes and produce results with higher resolutions.

Both the SLOSH and ADCIRC models are applied in my lab, depending on applications. Figure 2 shows that, as an example, the simulated storm surges in the NYC area from Hurricanes Irene (2011) and Sandy, using the ADCIRC model in this case, compare very well with the tidal gauge observations. In these simulations, we used high-resolution bathymetry and topography data, observed storm characteristics, as well as our new complete wind profile (Chavas et al. 2015) and a simple parametric pressure model (Holland 1980).

Rainfall

Hurricane rainfall is comparatively difficult to model because of its large spatial and temporal variation. Thus, most hurricane rainfall modelling applies full numerical weather prediction models (e.g., Lin et al. 2010b; Tuleya and DeMaria 2007). However, this approach requires large quantities of input data and has a high computational cost, so it is not effective for risk analysis.

Recently, simpler parametric models have been developed based on historical rainfall statistics (e.g., Lonfat et al. 2007; Tuleya et al. 2007) and physical
principles (e.g., Langousis and Veneziano 2009). The basic physics of hurricane rainfall is that it is determined mainly by the combination of environmental moisture and the speed of the storm updraft. The latter depends on low-level convergence due to surface friction, storm intensification, interactions with topography, and the background baroclinic state. A model that describes these processes has been shown to generate rainfall statistics comparable to the observations (Zhu et al. 2013).

Research in my lab is ongoing to evaluate and further develop this physical rainfall model, which can then be coupled with a hydrologic model (e.g., Cunha et al. 2012) to simulate inland flooding.

**Hurricane Risk**

Hazard models can be applied to simulated synthetic storms to generate large samples of hazards from which hazard probabilities can be estimated. For example, the ASCE building code has used such an approach to establish design wind maps (showing wind speeds for various return periods) for the entire US coast. Similarly, the Federal Emergency Management Agency (FEMA) developed flood maps depicting 100- and 500-year floodplains as a basis for the federal flood insurance policy. (Different storm and hazard models were used in these different applications.)

If the hurricane model used to generate synthetic storms draws on climate model–projected climate environments (Emanuel et al. 2008), one can estimate probabilistic hazards under future climates. We have performed such analysis for various coastal cities; for example, figure 3 shows our estimations of the storm surge level for NYC as a function of return period, under the observed current climate as well as climate model–estimated current climates and climate model–projected future climates. The results indicate a potentially significant increase of surge floods in the future due to climate change.

The hazard probabilities can also be combined with the estimated consequences of the hazards to quantify the risk. (The consequent damage/losses can be esti-
mated with vulnerability models such as the Hazus model developed by FEMA.) The risk is often expressed by the expectation (mean) of the loss in a year (e.g., Aerts et al. 2013), but the full probabilistic distribution of the loss, if available, is more informative. In the context of climate change and coastal development, this risk is likely increasing.

To obtain a temporally integrated measure, the overall loss is also typically quantified by its present value (PV), the sum of all discounted losses occurring over a given time horizon (e.g., the next 100 years). Then the risk can be considered as the mean or, better, the probability distribution of the PV of future losses.

**Benefits and Costs of Risk Mitigation Strategies**

The PV also provides a convenient metric for comparing the benefit and cost of risk mitigation strategies. The benefit can be considered as the PV of the future losses prevented by mitigation, and the cost is the PV of the total cost of the mitigation (including construction and maintenance). While the cost is largely deterministic, the benefit is random.

Most studies have focused on comparing the cost and the mean of the benefit (e.g., Aerts et al. 2014). We present a more informative probabilistic cost-benefit analysis, applied to various coastal flood mitigation strategies proposed for NYC. As shown in figure 4, for each strategy we estimate the full probability distribution of the benefit and plot its exceedance probability function to compare with the cost. The crossing of the curve of the benefit exceedance probability and the line showing the cost indicates the probability that the benefit is greater than the cost. The probabilities of getting any higher or lower benefits can also be easily read from the curve.

The probabilistic benefit-cost analysis thus provides adequate information for making management decisions for any specific risk tolerance (decisions made based on the mean implicitly assume “risk neutral”). Also, this risk management analysis has relied on the physically

*FIGURE 4* Estimated exceedance probability of the benefit (curve) compared to the cost (vertical line) for strategies S2a and S2b (top), strategy S2c (middle), and a strategy of elevating new houses on the floodplain by 6 feet (bottom) for New York City (NYC). S2a consists of three barriers to close off parts of NYC and New Jersey but preserves wetland dynamics of Jamaica Bay. S2b expands on S2a by adding a fourth barrier that closes off Jamaica Bay. S2c replaces three barriers from S2b with one large barrier in the outer NY harbor to protect a larger area. The details of these mitigation strategies are discussed in Aerts et al. (2014). The analyses account for projected coastal development and changes in storm activity and sea level over the 21st century. Current and future building stock data are obtained from the NYC Office of Emergency Management. Synthetic storm surge events are obtained from Lin et al. (2012) for the four climate models (CNRM, ECHAM, GFDL, and MIROC; see figure 3 for definitions), as shown by the return level curves in figure 3. The probabilistic sea level rise projection is based on Kopp et al. (2014); the three curves of the same color show results with sea level rise projected for the three IPCC AR5 (Intergovernmental Panel on Climate Change Fifth Assessment Report) emission scenarios (RCP 2.6, RCP 4.5, and RCP 8.5).
based risk assessment to account for the dynamic evolution of urban development, storm climatology change, and sea level rise.

**Future Research**

Although much remains unknown about how hurricanes, especially their frequency and size, will vary with the climate, risk assessment should continue to incorporate the state-of-the-art science to support risk management. Effective risk analysis will require more physical or physical-statistical methods for simulating synthetic storms. Hurricane rainfall models, especially those based on physics, need to be developed to estimate inland flood risk in a changing climate. Hurricane hazards are correlated (e.g., hurricane wind affects both storm surge and rainfall; coastal and inland flooding may interact), and multihazard approaches are needed to estimate how hazards will jointly evolve and how to deal with the joint risk.

In addition to engineering measures, urban planning and federal and private insurance play increasingly important roles in coastal risk mitigation. Establishing systematic and more integrated strategies may be the future direction for hurricane risk management.

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**References**


